Quantity discrimination, decision-making, and the role of early-life conditions in a lizard

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## Abstract

Quantity discrimination affects a range of behaviours that are essential for fitness including social interactions, navigation, and foraging. Animals use different cognitive systems to distinguish between quantities. The Approximate Number System (ANS) estimates, while the Object File System (OFS) tracks discrete items. In reptiles, quantity discrimination remained largely unexplored until recently, and the use of one system over the other can depend on the species or the context in which they are tested. Additionally, early life conditions can influence brain development and cognition, with potential effects on quantity discrimination and decision-making. Here, we tested the ability of the common garden skink (*Lampropholis guichenoti*) to discriminate between quantities and the effects of elevated prenatal GCs and incubation temperature on quantity discrimination and decision-making. We assessed quantity discrimination using a spontaneous choice test with food as a stimulus. We subjected lizards to five two-choice tests each differing in the number of items (1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4). Contrary to our predictions, we found no evidence of quantity discrimination in *L. guichenoti*. Furthermore, prenatal conditions did not influence quantity discrimination or decision-making. Despite these results, further investigation of quantity discrimination in live-prey-feeding reptiles and the impact of early conditions on other taxa remains an important area of research.

## Significance statement

Discriminating between quantities can be crucial for individual fitness, yet it remains poorly understood in reptiles. In this study, we investigated quantity discrimination in *Lampropholis guichenoti* using a spontaneous choice test with food as the stimulus. Contrary to our predictions, we found no evidence of quantity discrimination in this species. In addition, we explored the impact of early environmental factors, specifically prenatal corticosterone exposure and incubation temperature, on quantity discrimination and decision-making. However, we did not observe any effect of these early-life conditions on lizards’ behaviour. These results open new avenues for exploring the evolution of quantity discrimination in reptiles and identifying factors influencing cognitive development in this group. Further research should explore alternative methods, such as trained tasks, to better understand the mechanisms underlying quantity discrimination and decision-making in reptiles.

## Introduction

The ability to discriminate between quantities is a fundamental cognitive skill widely observed across the animal kingdom ([Vonk and Beran 2012](#ref-vonk2012bears); [Stancher et al. 2015](#ref-stancher2015numerical); [Beran and Parrish 2016](#ref-beran2016capuchin)). Quantidy discrimination can contribute to social decisions, mate selection, and foraging behaviour, which can be adaptive in numerous ecological contexts ([Lucon-Xiccato and Dadda 2017](#ref-lucon2017individual); [Nieder 2018](#ref-nieder2018evolution)). For instance, female lions (*Panthera leo*) use numerical information to assess the risk of confronting rival groups ([McComb et al. 1994](#ref-mccomb1994roaring)), male adult mealworms (*Tenebrio molitor*) select sites with scents of more females ([Carazo et al. 2009](#ref-carazo2009quantity)), and red-backed salamanders (*Plethodon cinereus*) prefer tubes containing larger numbers of prey ([Uller et al. 2003](#ref-uller2003salamanders)). Given the adaptive advantages of quantity discrimination, research has focused extensively on exploring the ability of different species to differentiate between quantities.

The main two experimental approaches in the study of quantity discrimination are spontaneous choice tests and training procedures ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). Spontaneous choice tests ascertain if animals can distinguish between two groups of biologically relevant stimuli that differ quantitatively (number, size, volume, etc) (Agrillo and Bisazza [2014](#ref-agrillo2014spontaneous); Cox and Montrose [2016](#ref-cox2016quantity)). In comparison, experiments that employ training procedures evaluate an animal’s ability to learn a numerical rule to receive a reward ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous); [Miletto Petrazzini et al. 2018](#ref-miletto2018quantity)). Both methods are believed to be complementary to each other, and both can provide different results even in the same species (Miletto Petrazzini et al. 2017; [2018](#ref-miletto2018quantity)).

Numerous reasons exist for why methods can lead to different results. First, spontaneous choice tests assume that one of the options presented is more adequate than the other (e.g. the group with more conspecifics or the larger amount of food) when this may not always be the case. For example, choosing groups of conspecifics with less individuals could be advantageous when food is scarce but disadvantageous when predators are abundant ([Yee et al. 2013](#ref-yee2013costs)). As such, context and motivation can be important drivers of decision-making that can change the way animals discriminate between quantities ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). Second, each method may engage distinct cognitive mechanisms when processing numerical information ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). Different procedures may shape how animals discriminate between quantities, making them more responsive towards certain quantity traits over others. Some tasks may encourage a focus on approximate magnitudes, while others may promote attention to individual items ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)).

In this regard, it is well recognised that two core systems underlie numerical cognition: the approximate number system (ANS) and the object file system (OFS) ([Hyde 2011](#ref-hyde2011two)). The ANS estimates the approximate magnitude of items within a set, with accuracy decreasing as the numerical difference between sets decreases — a principle known as Weber’s law ([Hyde 2011](#ref-hyde2011two)). In contrast, the OFS allows for the precise tracking of discrete items but is thought to be limited to small quantities, typically up to three or four ([Hyde 2011](#ref-hyde2011two)). The engagement of these systems depends not only on the numerical magnitude but also on contextual factors such as the availability of continuous variables (e.g., area, density, movement) and the nature of the task ([Stancher et al. 2015](#ref-stancher2015numerical)). The presence of such continuous cues typically favors ANS-based processing, while in their absence, the OFS is more likely to be employed ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). This often complicates the study of numerosity, as continuous traits must be carefully controlled to ensure the use of the OFS ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). In spontaneous choice tests, for instance, animals may rely on cumulative surface area rather than numerical differences when selecting between two sets of food items ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). To disentangle these cues, researchers often equate the total area of the sets while changing the number of items, forcing individuals to rely on numerical information alone ([Stancher et al. 2015](#ref-stancher2015numerical)).

Quantity discrimination studies have been traditionally focused on mammals, birds, and fishes despite the influence of numerical cognition on fitness across taxa ([Mehlis et al. 2015](#ref-mehlis2015quantification); [Nieder 2018](#ref-nieder2018evolution)). However, recent studies demonstrate that other vertebrates like amphibians or non-avian reptiles are also competent in numbers ([Uller et al. 2003](#ref-uller2003salamanders); [Stancher et al. 2015](#ref-stancher2015numerical); [Miletto Petrazzini et al. 2017](#ref-miletto2017quantitative)). For example, freshwater turtles (*Trachemys scripta* and *Mauremys sinensis*) and red-footed turtles (*Chelonoidis carbonaria*) can rapidly learn a quantity discrimination task, and Hermann’s tortoises (*Testudo hermanni*) can discriminate between large and small food quantities in a spontaneous choice test ([Gazzola et al. 2018](#ref-gazzola2018continuous)). In lizards, the Italian wall lizard (*Podarcis siculus*) failed to discriminate between different numbers of food items in a spontaneous choice test ([Miletto Petrazzini et al. 2017](#ref-miletto2017quantitative)), but succeeded in a trained quantity discrimination task ([Miletto Petrazzini et al. 2018](#ref-miletto2018quantity)). Shinglebacks (*Tiliqua rugosa*) exhibited spontaneous quantity discrimination using both discrete and continuous cues ([Szabo et al. 2024](#ref-szabo2024spontaneous)), while Gidgee skinks (*Egernia stokesii*) discriminated between items when they differed in number, but not when size was the main quantitative cue ([Szabo et al. 2021](#ref-szabo_spontaneous_2021)). These studies demonstrate that reptiles have cognitive abilities related to quantity discrimination that have been overlooked in the past, and that the use of the ANS versus the OFS can differ between species and in different contexts ([Szabo et al. 2021](#ref-szabo_spontaneous_2021)). However, cognitive performance is not solely dictated by species differences; developmental conditions can also shape an individual’s ability to process numerical information ([Vila-Pouca et al. 2019](#ref-vila_pouca_quantity_2019)).

Cognition can be strongly influenced by developmental conditions because the brain is particularly sensitive to environmental inputs in early life stages ([Zhu et al. 2004](#ref-zhu_prenatal_2004)). For instance, the temperature at which embryos develop can affect neuron density and learning abilities in different species of reptiles ([Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Amiel et al. 2017](#ref-amiel_effects_2017); [Dayananda and Webb 2017](#ref-dayananda_incubation_2017); [Siviter et al. 2017b](#ref-siviter_incubation_2017); [Abayarathna and Webb 2020](#ref-abayarathna_effects_2020)). Thermal effects on cognition may arise directly or indirectly through parental effects ([Crino et al. 2023](#ref-Crino_2023)). For example, temperatures outside the optimal range can trigger stress responses, leading to the release of glucocorticoids (GCs) ([Sapolsky et al. 2000](#ref-sapolsky_how_2000)), which may then be transmitted to offspring ([Crino et al. 2023](#ref-Crino_2023)). Elevated prenatal GCs can, in turn, influence cognition by altering brain function ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004); [Crino et al. 2014](#ref-crino_corticosterone_2014-learn); [Farrell et al. 2015](#ref-farrell_developmental_2015-learn); [Bebus et al. 2016](#ref-bebus_associative_2016); [Lui et al. 2017](#ref-lui2017chronic)). As such, the interaction between GCs and developmental temperature may be relevant in shaping reptile cognition. Most studies on the effects of GC exposure or elevated temperatures during development focus on learning and memory, but, to the best of our knowledge, only one study has investigated how early-life conditions can affect quantity discrimination despite its importance on animals’ lives (see [Vila-Pouca et al. 2019](#ref-vila_pouca_quantity_2019)). Furthermore, the interactive effects of prenatal GCs and temperature on cognitive abilities remain largely unexplored.

Here, we investigated quantity discrimination in the common garden skink (*Lampropholis guichenoti*) using a spontaneous choice test where lizards were presented with different number of food items. In addition, we examined how prenatal corticosterone (CORT) - the main GC in reptiles - and incubation temperature can affect quantity discrimination and decision-making in foraging contexts. To do so, we manipulated CORT concentration (CORT-treated or a sham control) in *L. guichenoti* eggs and incubated them under one of two temperature regimes (Cold - 23 ± 3ºC or Hot - 28 ± 3ºC) in a 2x2 factorial design. Then, we assessed numerical discrimination abilities on five tests that differed in the relative number of food items: 1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4 crickets. Previous studies showed that skink species can discriminate between different quantities of food using both the ANS and the OFS ([Szabo et al. 2021](#ref-szabo_spontaneous_2021), [2024](#ref-szabo2024spontaneous)). We predicted *L. guichenoti* to be able to discriminate between different number of crickets even when controlling by other continuous variables by other continuous variables like total length and area (i.e. by using the OFS). Furthermore, we predicted lizards’ decisions to be influenced by the early conditions they were subjected to. In this regard, we hypothesised that lizards incubated at higher temperatures would outperform those incubated at lower temperatures in the numerical discrimination task ([Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Amiel et al. 2017](#ref-amiel_effects_2017); [Vila-Pouca et al. 2019](#ref-vila_pouca_quantity_2019)). Furthermore, we predicted that increased CORT levels would impair numerical discrimination ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004)), with more pronounced effects at lower temperatures.

## Methods

#### Animal husbandry

*Breeding colony* – The lizards tested in our experiment came from a breeding colony established in the lab in 2019. The colony consisted of approximately 180 adults of *L. guichenoti* housed in communal containers (41.5 L x 30.5 W x 21 H cm) with six lizards (2 males and 4 females) per enclosure. Enclosures were provided with non-stick matting, shelter, and several small water dishes filled daily, and lizards were fed mid-size crickets (*Acheta domestica*) three days a week. Crickets were dusted with calcium weekly and multivitamins and calcium biweekly. Room temperatures were set to 22-24ºC, but to ensure a temperature gradient, we employed a heat chord and a heat lamp following a 12 h light:12 h dark cycle, keeping the warm side of enclosures at 32-34ºC.

*Egg collection and incubation* – Between mid-October 2023 to the end of February 2024, we placed small boxes (12.5 L x 8.3 W x 5 H cm) containing vermiculite on one side of the communal enclosures (see above) to provide females with a place to lay the eggs. We checked for eggs in the boxes three days a week. Egg length and width were measured with digital calipers to the nearest mm (± 0.1 mm), while mass was recorded with a digital scale (OHAUS, Model spx123) to the nearest g (± 0.001 g). Eggs were assigned a clutch number and an individual identity. Then we treated eggs with CORT or a vehicle control (see *Manipulating Early Thermal and CORT Environments* details below) and placed them in individual cups (80 mL) with moist vermiculite (12 g water to 4 g vermiculite). We covered the cups with plastic wrap to retain moisture and left the eggs in incubators (LATWIT 2X5D-R1160) programmed to two different thermal regimes (see *Manipulating Early Thermal and CORT Environments* details below) until hatching. Incubators were checked for the presence of hatchlings three times a week.

*Hatchlings* – Immediately after hatching, we measured Snout-Vent Length (SVL) and Tail Length (TL) with a ruler to the nearest mm (± 0.1 mm), and mass using a digital scale (OHAUS, Model spx123) to the nearest g (± 0.001 g). Hatchlings were then placed in individual enclosures (18.7L x 13.2W x 6.3H cm) provided with non-stick matting and a small water dish. During this period, they were given water daily and received 3-6 small *A. domestica* crickets three times a week. All care otherwise follows similar protocols to adults (see above).

#### Manipulating Early Thermal and CORT Environments

We manipulated CORT concentration in eggs and incubated them under one of two temperature regimes (Cold - 23 ± 3 ºC or Hot - 28 ± 3 ºC) in a 2x2 factorial design ([Fig. 1](#fig-Methods) A). Eggs were allocated to one of two different developmental stress treatments: CORT-treated eggs were topically supplied with 5 µL of a CORT solution (10 pg/mL). Control treatment eggs received an equal volume of 100% Ethanol. Corticosterone treatments were made by dissolving crystalline corticosterone (Sigma, Cat. No. C2505) in 100% ethanol. We selected doses based on previous studies where CORT treatment increased mean yolk CORT levels ~3.7x higher than control eggs in *Lampropholis delicata* ([Crino et al. 2024](#ref-crino2024eggs)). Then, eggs were incubated in one of the two previously mentioned temperature regimes (Cold or Hot) until hatching. These temperatures represent the upper and lower limit of the natural incubation temperatures for this species ([Qualls and Shine 2000](#ref-qualls2000post)).

The number of eggs per clutch assigned to each hormone and temperature treatment was counterbalanced in a partial split-clutch design. At least one egg per clutch to each treatment, and the remaining eggs were randomly assigned to one of the treatments. When we found less than four eggs in a clutch, we assigned each egg randomly to one of the treatments.

#### Numerical discrimination task

Lizards were acclimatised to the experimental arenas for two weeks before starting the numerical discrimination task (see below). The arenas were individual medium-size (41 L x 29.7 W x 22 H cm) plastic containers provided with a shelter (9 L x 6 W x 1.5 H cm) on one of the sides and a water dish in the center ([Fig. 1](#fig-Methods) B). Arenas were placed on seven different racks located in two experimental rooms. Each rack was associated with its own CCTV system (device model DVR-HP210475), allowing us to record lizards’ behaviour during the experiment. Despite the conditions in the experimental rooms were the same as in the colony room, we counterbalanced the number of lizards per treatment in each rack to control for any potential effects of the room or the position of the lizard in the rack. During acclimatisation and throughout the experiment, lizards were fed with only one cricket daily, dusted with calcium and multivitamins (see protocol below), and water was supplied *ad libitum*. The temperature of both rooms was set to 22-24ºC, but we also provided a temperature gradient (24-32°C) using a heat cord along the center of the arena and heat lamps in a 12 h light: 12 h dark cycle.

The numerical discrimination test consisted of a series of two-choice trials where lizards were presented with different numbers of food items. Each choice was placed on one of the two lateral platforms of a white 3D printed device (see [Fig. 1](#fig-Methods) B, C) and then covered with a transparent Petri dish to prevent the lizard from obtaining the food. We performed five tests that differed in the ratio between both choices of crickets. Specifically, we compared: 1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4 crickets. The food consisted of small frozen crickets (*A. domestica*) that were thawed and dusted with calcium and multivitamins. We decided to use frozen crickets to avoid movement that would affect lizard behaviour ([Cooper et al. 2024](#ref-cooper2024tell)). Lizards were habituated to eating frozen crickets for one month before the experiments.

The crickets used during the experiment were all the same size, but to control for some continuous traits we changed the orientation of the crickets as illustrated in [Fig. 1](#fig-Methods) D. This method was intended to control for length and total area (see Stancher et al. [2015](#ref-stancher2015numerical)). We tested if the length occupied by the crickets was similar in both choices (see *Supplementary Material - Control of size in both options*). Our results showed that except for the 1 VS 4 and 1 VS 3 tests, the difference in length between both choices was not different from zero. As such, discrimination between both choices in the rest of the tests (2 VS 4, 2 VS 3, 3 VS 4 crickets) would be produced by the OFS, not the ANS ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). In addition, after the experiments, we conducted another set of trials to test whether the orientation of the crickets could affect lizards’ choice, but we found no effect of orientation (see *Supplementary Material - Prey orientation test*).

To habituate lizards to the experimental conditions, frozen crickets were placed on top of one of the platforms and Petri dishes during each feeding for two weeks prior to experimental trials. The side where the food was placed was changed every day to avoid any side bias during the trials. However, to further control for side biases, the higher number of crickets was randomly placed on the right or the left platform. We also counterbalanced the number of individuals per treatment tested in the same type of trial each day.

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| Fig 1— Experimental design. Panel (**A**) shows the early environment manipulation procedures. (**B**) illustrates the arena where the tests were performed, while panel (**C**) indicates the measurements of the platform used for the experiments. Finally, panel (**D**) displays the types of numerical tests used and the orientation of the crickets in each test. |

All tests were done between 1000-1200 hours when the lizards were most active. Each trial was performed daily for five days between the 17th and 22nd of May 2024. We recorded three main variables: i) *Latency*, defined as the time between the start of the test - when the platform was left in the enclosure - until the first interaction with one of the options; ii) First choice of the lizard (*Choice*), recorded as 1 if the lizard interacted first with the larger amount or 0 if not; and iii) *Interest* shown for the higher amount of food (detailed below). We considered that the lizard interacted with the food when it touched the Petri dish with its snout or when the front half of the body was on top of the platform. For five minutes after the first interaction with one of the options, we recorded the time spent interacting with that option for a maximum of five minutes; we did this for both amounts of food independently of what was the first choice. We measured the interest shown for the higher amount of food (*Interest*) by subtracting the time interacting with the option with fewer crickets to the time spent interacting with the larger amount of food. If there was no interaction with one of the options during the test, we considered the time spent as zero for that option. When there was no interaction with any of the choices, both *Latency*, *Choice*, and *Interest* were noted as NA. We also considered Interest as NA in a few cases where the animals managed to lift the dish and eat the prey; Latency and Choice were recorded and employed in the analyses. We excluded from the analyses all the individuals that did not make any choice in three or more tests. All the analyses were by one observer (PR), who was blind to the treatment of the lizards, but not the type of test or the number of crickets because the videos were analysed manually.

Motivation plays a key role in animals’ performance in spontaneous choice tests ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous); [Bisazza et al. 2014](#ref-bisazza2014experim)). To ensure that lizards remained motivated to forage, they were provided with only one cricket during both acclimatisation and the numerical task (see above). During acclimatisation, lizards were fed at the same time each day as the experiments were conducted. In the numerical task, lizards received a cricket immediately after the test and then fasted for more than 20 hours, which we expected would help standardise fasting levels across individuals. To further control for motivation, we excluded from our analyses any trials in which lizards did not interact with any options or did not eat the cricket provided after the test (n = 0 in both cases). Consequently, we do not consider motivation to be a major factor influencing our results (but see Discussion).

#### Statistical analyses

In our analyses, we fitted a multivariate Bayesian multilevel model using the brm function from the *brms* package ([Bürkner 2017](#ref-burkner2017brms)) in R (version 2.8.2) ([R Core Team 2021](#ref-R)). We ran four parallel MCMC chains of 3000 iterations for each model, with a warmup period of 1000 iterations. We checked that all MCMC chains converged (Rhat < 1.2) and were mixing effectively to ensure we had >1000 effective samples from the posterior distribution.

We modelled the three main recorded behaviours: *Latency*, *Choice*, and *Interest* as the response variables. We assumed normal distributions for Latency (log-transformed) and Interest [family = gaussian()]. The error structure for Choice was modeled using a Bernoulli distribution with a logit link function [family = Bernoulli(link = ‘logit’)]. We included test (1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4), hormone (CORT versus Control), incubation temperature (Cold versus Hot), and the three-way interaction as fixed factors. We also included in our predictors sex, and age. We did not find any effect of sex or age on Choice or Interest, but we found an effect on Latency (see Results). Regardless, we included both factors in all models. Age was centered to zero in the model, and we averaged the predicted values for males and females.

We included lizard identity and clutch as random factors. *L. guichenoti* lays up to two clutches per year ([Joss and Minard 1985](#ref-joss1985reproductive)). Since egg collection was done during half of the breeding season, each clutch likely came from a unique mother, and so, clutch identity captures potential maternal effects.

We used the posterior distributions of parameters from these models to test for between treatment differences in the ability to discriminate different numbers of crickets for each of the numerical tests. Because the posterior distributions were not always normally distributed, we report the median as the main measure of central tendency. We used the 95% Highest Posterior Density Intervals (95% HPDI) using the hdi function in bayestestR ([Makowski et al. 2019](#ref-bayestestR)) to test if the contrasts between treatments for all the variables, or the *Interest* per each test was different form zero. Given Choice was Bernoulli, we modified our null hypotheses to test if differed from a probability of 0.5 as there were only two possible choices and if animals were choosing randomly we would predict each choice would have a 50% probability.

#### Ethical note

Subjects were collected from a breeding colony that had been kept in the lab since 2019. All animals in this experiment were provided humane laboratory housing, thermoregulation opportunities, and light and humidity conditions (see above for details). Lizards in the colony received five to seven crickets per individual three times a week while the subjects in the experiment were fed once per day. All lizards were handled minimally to avoid stress. Experimental procedures and laboratory housing complied with Australian law and were approved by the Australian National University Animal Experimentation Ethics Committee (A2022\_33). Upon completion of experimental trials, lizards were kept in their enclosure and will be euthanized following standard humane procedures once they reach the humane endpoint.

## Results

Overall, males showed lower latencies than females (median of the estimated effect of sex = -0.45, 95% HPDI = [-0.89, -0.02]), and older individuals also made decisions faster (mean estimated effect of age = 0.06, 95% HPDI = [0.01, 0.11]; see Table S3 in *Supplementary Material*). However, we did not see any effect of age or sex on *Choice* or *Interest* (see *Supplementary Material*).

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| Fig 2— Estimates of log-latency (Latency), the probability of choosing the larger number of crickets first (Choice), and the estimated interest in the larger number of crickets (Interest) for each of the numerical tests performed across different developmental treatments. The x-axis represents the estimate, and the y-axis is the posterior density of the estimates. The different colours indicate the different treatments. Points and bars represent the median and 95% Highest Density Intervals (95% HPDI) of the estimates, respectively. Vertical dashed lines in Choice and Interest graphs values 0.5 and 0, respectively. Asterisks indicate values significantly different from 0. |

Neither temperature, CORT, or their interaction affected performance in any of the tests, nor were there any clear patterns suggestive of an effect of the developmental environment on numerical discrimination (see Table 1 and [Fig. 2](#fig-results)). Except for Hot-CORT lizards in 1 VS 3 tests or Cold-Control lizards in 2 VS 3 tests, the predicted probability of choosing the larger number of crickets first was not different from 0.5 ([Fig. 2](#fig-results); but also see Table S1 and Table S2 in *Supplementary Material*). Similarly, interest in the larger number of crickets (*Interest*) was not different from 0 in any of the tests ([Fig. 2](#fig-results); but also see Table S1 and Table S2 in *Supplementary Material*).

*Table 1. Effects of temperature, CORT, and their interaction on Latency, Choice, and Interest in each of the numerical discrimination tests. The table shows the contrasts for each predictor (Temperature = [medianHot - medianCold]; Hormone = [medianControl - medianCORT]; and their Interaction = [(medianHot-Control - medianHot-CORT) - (medianCold-Control - medianCold-CORT)]). 95% Highest Density Intervals (95% HPDI) test the hypothesis that contrasts are different from zero.*

|  | | Tests | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Predictor | 1VS4 | 1VS3 | 2VS4 | 2VS3 | 3VS4 |
| Latency | Hormone | -0.3 [-1.39 , 0.8] | -0.1 [-1.14 , 0.82] | 0 [-0.97 , 0.97] | -0.2 [-1.08 , 0.77] | -0.3 [-1.17 , 0.52] |
| log(latency) | Temperature | -0.3 [-1.45 , 0.74] | -0.2 [-1.23 , 0.73] | -0.4 [-1.36 , 0.57] | -0.4 [-1.33 , 0.52] | -0.1 [-0.94 , 0.77] |
|  | Interaction | -0.8 [-1.94 , 0.4] | -0.5 [-1.75 , 0.64] | -0.5 [-1.7 , 0.74] | -0.4 [-1.57 , 0.79] | 0 [-1.2 , 1.23] |
| Choice | Hormone | 0 [-0.45 , 0.43] | 0 [-0.43 , 0.53] | 0 [-0.33 , 0.41] | 0.1 [-0.36 , 0.45] | 0.1 [-0.25 , 0.48] |
| log(odds) | Temperature | 0.1 [-0.34 , 0.54] | 0.2 [-0.29 , 0.66] | 0 [-0.35 , 0.39] | -0.3 [-0.66 , 0.14] | 0.2 [-0.2 , 0.53] |
|  | Interaction | -0.3 [-0.79 , 0.21] | -0.4 [-0.87 , 0.07] | 0.1 [-0.4 , 0.61] | -0.2 [-0.72 , 0.26] | -0.1 [-0.6 , 0.37] |
| Interest | Hormone | -1.3 [-59.55 , 54.62] | -11.9 [-83.67 , 64.05] | 1.5 [-59.81 , 65.18] | 2.5 [-78.71 , 82.35] | 40.3 [-19.82 , 99.74] |
|  | Temperature | -11.3 [-68.87 , 46.46] | 22.6 [-50.44 , 95.41] | -5.1 [-68.08 , 56.31] | -22.4 [-102.22 , 59.51] | 3.5 [-55.15 , 65.4] |
|  | Interaction | 19.8 [-56.91 , 94.76] | -56.5 [-133.25 , 20.49] | 34.5 [-41.72 , 110.47] | -70.2 [-145.33 , 6.71] | -23.9 [-100.36 , 55.25] |

## Discussion

Contrary to our predictions that numerical cues would influence foraging decisions, and that elevated prenatal CORT or cold incubation temperatures would impair numerical discrimination, we found no significant differences across tests or treatments. Our results indicate that lizards did not discriminate between different numbers of crickets, nor did their performance vary under our experimental conditions. Overall, these findings suggest that *L. guichenoti* do not use numerical or other potential quantitative cues for foraging decisions and that any decision making was not affected by early environment.

#### Foraging context may influence spontaneous quantity discrimination in reptiles

#### Lack of numerical discrimination in spontaneous tests may be due to L. guichenoti being insectivorous. In studies where reptiles discriminated between different amounts of food, the relevant stimuli involved either vegetables (Gazzola et al. 2018; Szabo et al. 2021) or large quantities (e.g., 5 vs. 10) (Recio et al. 2021). In contrast, when Podarcis siculus were presented different numbers of Musca domestica larvae in a spontaneous choice test, the lizards failed to discriminate between quantities despite showing quantity discrimination when prey size was the main cue (Miletto Petrazzini et al. 2017) or when tested using training procedures (Miletto Petrazzini et al. 2018). Notably, the numbers of food items employed in Miletto Petrazzini et al. (2017) were always fewer than four. Spontaneous choice tests assume that animals should select the most appropriate quantity, which may not necessarily be the largest one (Agrillo and Bisazza 2014). This occurs if the costs of selecting the larger option outweigh the benefits. If capturing larger prey demands more time or energy, or if success rates remain similar regardless of prey quantity, animals may not exhibit a preference for larger quantities (Agrillo and Bisazza 2014). As a result, even if diet might not affect quantity discrimination abilities, insectivorous lizards might not have evolved a preference for larger patches of prey, at least with small numbers (see Recio et al. 2021).

Previous research showed that other species within the Scincidae family use exclusively the OFS in spontaneous discrimination tests (Szabo et al. 2021). Here, we aimed to investigate whether L. guichenoti could discriminate between different number of crickets in a spontaneous choice test relying exclusively on the OFS. To ensure that lizards decision relied on tracking discret items rather than using non-numerical cues, we controlled for total length and area — two variables that could influence ANS processing. We did this by rotating the position of the crickets in the smaller-choice option, making the total area comparable in both choices (Agrillo and Bisazza 2014; Stancher et al. 2015; Cooper et al. 2024). Absence of discrimination can therefore be explained by L. guichenoti relying on the ANS for quantity discrimination. Nonetheless, in two of our tests (1 VS 4 and 1 VS 3 crickets) cricket rotation was not sufficient to control for total length (see Supplementary Material - Control of size in both options). Yet, we still did not find quantity discrimination in L. guichenoti which suggests that neither the OFS nor the ANS were used. Instead, our results likely reflect a genuine lack of quantity discrimination in this species, at least in spontaneous choice tests.

#### Foraging behaviour is robust to early environmental experiences

Although the effects of early environment on cognition are widely studied, little attention has been paid to its impacts on numerical discrimination and decision-making. We found that decision-making was not influenced by CORT elevations or incubation temperature, as latency to make a choice did not vary across prenatal conditions. This suggests that L. guichenoti may be robust to these early-life factors, at least in the context of foraging decisions. Previous studies have reported that pine snakes (Pituophis melanoleucus) incubated at low temperatures were slower and less proficient in capturing prey (Burger 1991), but cold incubated bearded dragons (Pogona vitticeps) were faster at approaching a novel object at least at a young age (Siviter et al. 2017a). Maternal transmitted GCs are also known to reduce exploration and neophilia in different taxa (Koolhaas et al. 1999; Hope et al. 2018). Additionally, both prenatal CORT and incubation temperature can influence metabolic rate (MR), which in turn could affect motivation in food-based learning paradigms (Noble et al. 2018; Cossin-Sevrin et al. 2022; but see Trnik et al. 2011; Crino et al. 2014). In our design, we habituated lizards to the test conditions for two weeks before the experiment to minimise neophilia. And to control for motivation, we standardised hunger levels by providing only one cricket per day and fasting lizards for over 20 hours before testing. Additionally, we excluded trials where lizards failed to interact with either option or refused to eat the cricket provided after testing. These measures likely minimised variation in decision latency due to differences in exploration, neophilia, or hunger levels, which could explain why we did not detect an effect of prenatal conditions. Interestingly, we found that males and older lizards made decisions faster, although these factors were not central to our main hypotheses. However, it is possible that sex and age interact with early-life conditions in shaping behavioral responses. Future research should investigate potential interactions between developmental environment, sex, and age to better understand how these factors influence decision-making in reptiles.

Prenatal treatments did not influence quantity discrimination in *L. guichenoti* in our experiment. However, since none of the groups showed any kind of quantity discrimination in our tests, we cannot determine whether prenatal conditions affected the lizards’ numerical abilities or not; and we cannot discount the possibility that early environmental factors may affect quantity discrimination under other approaches or contexts. Nonetheless, to the best of our knowledge there is only one study examining how developmental conditions influence numerical abilities (Vila-Pouca et al. 2019). Vila-Pouca et al (2019) found that Port Jackson sharks (*Heterodontus portusjacksoni*) incubated at warmer temperatures learned a numerical rule faster than cold-incubated individuals. Given the potent effects of early environment on cognition and brain development (Szuran et al. 1994; Zhu et al. 2004; Amiel and Shine 2012; Clark et al. 2014; Amiel et al. 2014; Lui et al. 2017; Amiel et al. 2017), it is crucial to explore how early environmental conditions shape numerical abilities across taxa.

#### Conclusion

Our study was focused on investigating if *L. guichenoti* could use the OFS to discriminate between different number of food items. Additionally, we were interested in exploring the impact of prenatal conditions on numerical abilities and decision-making in reptiles. Our findings suggest that *L. guichenoti* does not rely on numerical information for foraging decisions and that their performance and decision-making does not vary due to prenatal temperature or CORT exposure. Our findings suggest that decision-making can be robust to early environmental conditions, at least in the context of foraging.

The absence of numerical discrimination in *L. guichenoti* is consistent with previous studies showing that insectivorous reptiles fail in spontaneous choice tests. However, it is critical to note that the methodologies employed in this study may not have fully captured the nuances of numerical cognition in *L. guichenoti.* Therefore, we recommend that future studies employ a broader array of tests and paradigms to more comprehensively assess numerical competence in this and related species. Furthermore, it would be relevant to study the effect of early environment on quantity discrimination to advance our understanding of numerosity across taxa.

## Data accessibility

All data, data description, and R code are available in public repository <https://github.com/Pablo-Recio/CORT-Temp_Numerical>.

## Declaration of AI use

We declare Chat GPT was used for questions related to coding and data analyses. All other parts of the manuscript were written by the authors and those parts where AI were used were checked and modified accordingly by the authors.

## Authors’ contributions

PR: conceptualization, methodology, data collection, data curation, formal analysis, writing—original draft, writing—review and editing; DL: data collection, writing—review and editing; OC: conceptualization, writing—review and editing; CF: conceptualization, funding acquisition, writing—review and editing; AP: data collection, writing—review and editing; DN: conceptualization, methodology, funding acquisition, project administration, resources, supervision, writing—review and editing.  
All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

## Conflict of interest declaration

We declare we have no competing interests.

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## References

Abayarathna T, Webb JK (2020) Effects of incubation temperatures on learning abilities of hatchling velvet geckos. Animal Cognition 23:613–620. <https://doi.org/10.1007/s10071-020-01365-4>

Agrillo C, Bisazza A (2014) Spontaneous versus trained numerical abilities. A comparison between the two main tools to study numerical competence in non-human animals. Journal of neuroscience methods 234:82–91

Amiel JJ, Bao S, Shine R (2017) The effects of incubation temperature on the development of the cortical forebrain in a lizard. Animal Cognition 20:117–125. <https://doi.org/10.1007/s10071-016-0993-2>

Amiel JJ, Lindström T, Shine R (2014) Egg incubation effects generate positive correlations between size, speed and learning ability in young lizards. Animal Cognition 17:337–347. <https://doi.org/10.1007/s10071-013-0665-4>

Amiel JJ, Shine R (2012) Hotter nests produce smarter young lizards. Biology Letters 8:372–374. <https://doi.org/10.1098/rsbl.2011.1161>

Bebus SE, Small TW, Jones BC, et al (2016) Associative learning is inversely related to reversal learning and varies with nestling corticosterone exposure. Animal Behaviour 111:251–260. <https://doi.org/10.1016/j.anbehav.2015.10.027>

Beran MJ, Parrish AE (2016) Capuchin monkeys (cebus apella) treat small and large numbers of items similarly during a relative quantity judgment task. Psychonomic bulletin & review 23:1206–1213

Bisazza A, Agrillo C, Lucon-Xiccato T (2014) Extensive training extends numerical abilities of guppies. Animal cognition 17:1413–1419

Bürkner P-C (2017) Brms: An r package for bayesian multilevel models using stan. Journal of statistical software 80:1–28

Cantlon JF, Platt ML, Brannon EM (2009) Beyond the number domain. Trends in cognitive sciences 13:83–91

Carazo P, Font E, Forteza-Behrendt E, Desfilis E (2009) Quantity discrimination in tenebrio molitor: Evidence of numerosity discrimination in an invertebrate? Animal Cognition 12:463–470

Chittka L, Geiger K (1995) Can honey bees count landmarks? Animal Behaviour 49:159–164

Clark BF, Amiel JJ, Shine R, et al (2014) Colour discrimination and associative learning in hatchling lizards incubated at “hot” and “cold” temperatures. Behavioral Ecology and Sociobiology 68:239–247. <https://doi.org/10.1007/s00265-013-1639-x>

Coomber P, Crews D, Gonzalez-Lima F (1997) Independent effects of incubation temperature and gonadal sex on the volume and metabolic capacity of brain nuclei in the leopard gecko (Eublepharis macularius), a lizard with temperature-dependent sex determination. The Journal of Comparative Neurology 380:409–421. [https://doi.org/10.1002/(SICI)1096-9861(19970414)380:3<409::AID-CNE9>3.0.CO;2-6](https://doi.org/10.1002/(SICI)1096-9861(19970414)380:3%3c409::AID-CNE9%3e3.0.CO;2-6)

Cooper TL, Pardo-Sanchez J, Sosnowski MJ, et al (2024) How to tell more is more: Quantity discrimination in eastern box turtles (emydidae: Terrapene carolina). Journal of Herpetology 58:1–15

Cossin-Sevrin N, Hsu B-Y, Marciau C, et al (2022) Effect of prenatal glucocorticoids and thyroid hormones on developmental plasticity of mitochondrial aerobic metabolism, growth and survival: An experimental test in wild great tits. Journal of Experimental Biology 225:jeb243414

Crino OL, Bonduriansky R, Martin LB, Noble DWA (2023) A conceptual framework for understanding stressinduced physiological and transgenerational effects on population responses to climate change. Evolution Letters

Crino OL, Driscoll SC, Ton R, Breuner CW (2014) Corticosterone exposure during development improves performance on a novel foraging task in zebra finches. Animal Behaviour 91:27–32. <https://doi.org/10.1016/j.anbehav.2014.02.017>

Crino O, Wild KH, Friesen CR, et al (2024) From eggs to adulthood: Sustained effects of early developmental temperature and corticosterone exposure on physiology and body size in an australian lizard

Dayananda B, Webb JK (2017) Incubation under climate warming affects learning ability and survival in hatchling lizards. Biology Letters 13:20170002. <https://doi.org/10.1098/rsbl.2017.0002>

Farrell TM, Neuert MAC, Cui A, MacDougall-Shackleton SA (2015) Developmental stress impairs a female songbird’s behavioural and neural response to a sexually selected signal. Animal Behaviour 102:157–167. <https://doi.org/10.1016/j.anbehav.2015.01.018>

Gazzola A, Vallortigara G, Pellitteri-Rosa D (2018) Continuous and discrete quantity discrimination in tortoises. Biology letters 14:20180649

Haq SU, Bhat UA, Kumar A (2021) Prenatal stress effects on offspring brain and behavior: Mediators, alterations and dysregulated epigenetic mechanisms. Journal of Biosciences 46:34. <https://doi.org/10.1007/s12038-021-00153-7>

Hyde DC (2011) Two systems of non-symbolic numerical cognition. Frontiers in human neuroscience 5:150

Jessop TS, Lane ML, Teasdale L, et al (2016) Multiscale evaluation of thermal dependence in the glucocorticoid response of vertebrates. The American Naturalist 188:342–356

Joss J, Minard J (1985) On the reproductive cycles of lampropholis guichenoti and l. Delicata (squamata: Scincidae) in the sydney region. Australian Journal of Zoology 33:699–704

Lin F-C, Shaner P-JL, Hsieh M-Y, et al (2024) Trained quantity discrimination in the invasive red-eared slider and a comparison with the native stripe-necked turtle. Animal Cognition 27:26

Lin F-C, Whiting MJ, Hsieh M-Y, et al (2021) Superior continuous quantity discrimination in a freshwater turtle. Frontiers in Zoology 18:1–11

Lucon-Xiccato T, Dadda M (2017) Individual guppies differ in quantity discrimination performance across antipredator and foraging contexts. Behavioral Ecology and Sociobiology 71:1–9

Lui E, Salim M, Chahal M, et al (2017) Chronic corticosterone-induced impaired cognitive flexibility is not due to suppressed adult hippocampal neurogenesis. Behavioural brain research 332:90–98

Makowski D, Ben-Shachar MS, Lüdecke D (2019) bayestestR: Describing effects and their uncertainty, existence and significance within the bayesian framework. Journal of Open Source Software 4:1541. <https://doi.org/10.21105/joss.01541>

McComb K, Packer C, Pusey A (1994) Roaring and numerical assessment in contests between groups of female lions, panthera leo. Animal Behaviour 47:379–387

Mentesana L, Hau M (2022) Glucocorticoids in a warming world: Do they help birds to cope with high environmental temperatures? Hormones and Behavior 142:105178

Miletto Petrazzini ME, Bertolucci C, Foà A (2018) Quantity discrimination in trained lizards (podarcis sicula). Frontiers in psychology 9:274

Miletto Petrazzini ME, Fraccaroli I, Gariboldi F, et al (2017) Quantitative abilities in a reptile (podarcis sicula). Biology Letters 13:20160899

Nieder A (2018) Evolution of cognitive and neural solutions enabling numerosity judgements: Lessons from primates and corvids. Philosophical Transactions of the Royal Society B: Biological Sciences 373:20160514

Nieder A (2005) Counting on neurons: The neurobiology of numerical competence. Nature reviews neuroscience 6:177–190

Noble DWA, Stenhouse V, Schwanz LE (2018) Developmental temperatures and phenotypic plasticity in reptiles: A systematic review and meta-analysis: Incubation temperature and plasticity. Biological Reviews 93:72–97. <https://doi.org/10.1111/brv.12333>

Plotnik JM, Brubaker DL, Dale R, et al (2019) Elephants have a nose for quantity. Proceedings of the National Academy of Sciences 116:12566–12571

Qualls FJ, Shine R (2000) Post-hatching environment contributes greatly to phenotypic variation between two populations of the australian garden skink, lampropholis guichenoti. Biological Journal of the Linnean Society 71:315–341

R Core Team (2021) [R: A language and environment for statistical computing](https://www.R-project.org/). R Foundation for Statistical Computing, Vienna, Austria

Racic A, Tylan C, Langkilde T (2020) Effects of temperature on plasma corticosterone in a native lizard. Scientific Reports 10:16315. <https://doi.org/10.1038/s41598-020-73354-z>

Recio P, Rodrı́guez-Ruiz G, López P, Martı́n J (2021) Prey quantity discrimination and social experience affect foraging decisions of rock lizards. Behavioral Ecology and Sociobiology 75:33. <https://doi.org/10.1007/s00265-021-02979-5>

Sapolsky RM, Romero LM, Munck AU (2000) How Do Glucocorticoids Influence Stress Responses? Integrating Permissive, Suppressive, Stimulatory, and Preparative Actions. 21:

Siegel A G. J. (ed) (2006) Basic neurochemistry. Molecular, cellular and medical aspects. Elsevier Academic Press

Soldati F, Burman OH, John EA, et al (2017) Long-term memory of relative reward values. Biology Letters 13:20160853

Stancher G, Rugani R, Regolin L, Vallortigara G (2015) Numerical discrimination by frogs (bombina orientalis). Animal Cognition 18:219–229

Szabo B, Noble DWA, McCloghry KJ, et al (2021) Spontaneous quantity discrimination in a family-living lizard. Behavioral Ecology 32:686–694. <https://doi.org/10.1093/beheco/arab019>

Szuran T, Zimmermann E, Welzl H (1994) Water maze performance and hippocampal weight of prenatally stressed rats. Behavioural Brain Research 65:153–155. <https://doi.org/10.1016/0166-4328(94)90100-7>

Uller C, Jaeger R, Guidry G, Martin C (2003) Salamanders (plethodon cinereus) go for more: Rudiments of number in an amphibian. Animal cognition 6:105–112

Vila-Pouca C, Gervais C, Reed J, et al (2019) Quantity discrimination in Port Jackson sharks incubated under elevated temperatures. Behavioral Ecology and Sociobiology 73:93. <https://doi.org/10.1007/s00265-019-2706-8>

Vila-Pouca C, Gervais C, Reed J, Brown C (2018) Incubation under Climate Warming Affects Behavioral Lateralisation in Port Jackson Sharks. Symmetry 10:184. <https://doi.org/10.3390/sym10060184>

Vonk J, Beran MJ (2012) Bears ‘count’too: Quantity estimation and comparison in black bears, ursus americanus. Animal behaviour 84:231–238

Zhu Z, Li X, Chen W, et al (2004) Prenatal stress causes gender-dependent neuronal loss and oxidative stress in rat hippocampus. Journal of Neuroscience Research 78:837–844. <https://doi.org/10.1002/jnr.20338>

# Supplementary Material

#### Effects of treatments on numerical discrimination using the estimates and the raw data

*Table S1.- Median and 95% Highest Density Intervals (95% HPDI) of the estimated probability of choosing first the higher amount (Choice) and the estimated interest for the higher amount of food (Interest) per treatment group for each of the numerical tests performed. 95% HPDI test the hypothesis that Choice = 0.5, and Interest = 0, which would indicate a preference towards one of choices.*

|  | | Choice | | Interest | |
| --- | --- | --- | --- | --- | --- |
| Test | Treatment | Median | 95% HPDI | Median | 95% HPDI |
| 1VS4 | Cold-CORT (n = 20) | 0.33 | [0.11 , 0.57] | 8.54 | [-30.61 , 49.35] |
|  |  | 0.48 | [0.23 , 0.72] | -2.77 | [-40.84 , 34.65] |
|  |  | 0.60 | [0.34 , 0.84] | -12.86 | [-52.24 , 28.73] |
|  |  | 0.43 | [0.2 , 0.69] | -4.39 | [-42.39 , 35.1] |
| 1VS3 | Cold-CORT (n = 20) | 0.39 | [0.15 , 0.64] | -19.49 | [-59.75 , 20.88] |
|  |  | 0.65 | [0.4 , 0.85] | -2.37 | [-39.95 , 36.71] |
|  |  | 0.81 | [0.61 , 0.96] | 31.17 | [-5.11 , 72.4] |
|  |  | 0.64 | [0.38 , 0.87] | -8.24 | [-49.13 , 31.43] |
| 2VS4 | Cold-CORT (n = 20) | 0.50 | [0.24 , 0.75] | 12.55 | [-27.29 , 52.49] |
|  |  | 0.48 | [0.24 , 0.72] | -3.36 | [-41.75 , 33.41] |
|  |  | 0.45 | [0.21 , 0.71] | -9.97 | [-48.1 , 29.59] |
|  |  | 0.55 | [0.3 , 0.8] | 8.66 | [-30.96 , 47.03] |
| 2VS3 | Cold-CORT (n = 20) | 0.60 | [0.32 , 0.83] | -9.77 | [-50.39 , 29.78] |
|  |  | 0.76 | [0.53 , 0.93] | 27.65 | [-11.07 , 65.46] |
|  |  | 0.44 | [0.19 , 0.7] | 3.63 | [-38.07 , 42] |
|  |  | 0.37 | [0.13 , 0.61] | -29.13 | [-69.44 , 7.53] |
| 3VS4 | Cold-CORT (n = 20) | 0.41 | [0.17 , 0.67] | -30.29 | [-72.18 , 8.75] |
|  |  | 0.59 | [0.34 , 0.82] | 21.88 | [-15.53 , 60.84] |
|  |  | 0.65 | [0.39 , 0.87] | -14.01 | [-54.51 , 27.79] |
|  |  | 0.70 | [0.46 , 0.9] | 14.21 | [-26.74 , 52.95] |

*Table S2.- Performance of each treatment in each of the numerical tests using the raw data. For the variable Latency and Interest, we show the median and the 95% CI. For the variable Choice, we show the proportion of individuals that chose the higher number of crickets first.*

|  | | | | Tests |  | |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Treatment | 1 VS 4 | 1 VS 3 | 2 VS 4 | 2 VS 3 | 3 VS 4 |
| Latency | Hot-Control (n = 20) | 595.5 [55.88 , 1593.72] | 721.25 [192.5 , 2074.55] | 622.8 [74.23 , 1447.22] | 666.35 [84.63 , 2311.7] | 742.2 [71.33 , 2344.85] |
|  | Hot-CORT (n = 20) | 1235.7 [257.98 , 4483.92] | 1011.5 [203.12 , 2379.73] | 852.4 [115.38 , 2527.57] | 840.9 [98.2 , 2524.95] | 1360.25 [145.43 , 6131.73] |
|  | Cold-Control (n = 20) | 663.35 [84.93 , 2605.7] | 729.95 [92.8 , 3099.77] | 630.5 [94.1 , 2500.82] | 575 [70.75 , 1679.95] | 491.15 [24.63 , 1915.57] |
|  | Cold-CORT (n = 20) | 880.25 [29.75 , 4557.85] | 760.3 [60.08 , 3493.4] | 703 [30.88 , 3522.77] | 962.15 [35.93 , 4747.52] | 1031.05 [19.88 , 4106.82] |
| Choice | Hot-Control (n = 20) | 8 | 12 | 10 | 7 | 13 |
|  | Hot-CORT (n = 20) | 11 | 15 | 9 | 9 | 11 |
|  | Cold-Control (n = 20) | 10 | 13 | 10 | 15 | 12 |
|  | Cold-CORT (n = 20) | 8 | 9 | 11 | 12 | 9 |
| Interest | Hot-Control (n = 20) | -6.5 [-126.97 , 163.07] | -10.68 [-180.9 , 113.25] | 6.6 [-85.05 , 162.3] | -31.1 [-118.62 , 56.62] | 12.05 [-186.6 , 228.85] |
|  | Hot-CORT (n = 20) | -15.11 [-152.65 , 61.45] | 28.65 [-152.27 , 185.65] | -12.74 [-120.8 , 182] | 1.68 [-108.4 , 120.55] | -15.71 [-148 , 84.4] |
|  | Cold-Control (n = 20) | -2.75 [-141.42 , 204.65] | -3.05 [-152.55 , 179.07] | -3.95 [-142.12 , 104] | 27.25 [-77.38 , 130] | 21.55 [-101 , 164.22] |
|  | Cold-CORT (n = 20) | 12.9 [-188.15 , 195.67] | -14.15 [-203.8 , 123.02] | 17.6 [-105.78 , 186.17] | -4.68 [-119.05 , 79.8] | -24.84 [-182.8 , 74.95] |

#### Model results

*Table S3A.- Summary of the model fitted for loglatency (Latency)*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_loglatency\_Intercept | 6.47 | 6.47 | 0.31 | 5.96 | 7.00 | 1.00 | 4547.93 | 6871.87 |
| b\_loglatency\_test\_type1VS3 | -0.03 | -0.03 | 0.21 | -0.37 | 0.31 | 1.00 | 5851.20 | 8069.68 |
| b\_loglatency\_test\_type2VS4 | -0.13 | -0.13 | 0.21 | -0.46 | 0.21 | 1.00 | 5607.53 | 8779.16 |
| b\_loglatency\_test\_type2VS3 | -0.02 | -0.02 | 0.21 | -0.36 | 0.33 | 1.00 | 5792.88 | 8099.56 |
| b\_loglatency\_test\_type3VS4 | -0.07 | -0.07 | 0.21 | -0.42 | 0.27 | 1.00 | 5394.76 | 8113.94 |
| b\_loglatency\_tempHot | 0.05 | 0.05 | 0.45 | -0.69 | 0.80 | 1.00 | 4240.55 | 6468.22 |
| b\_loglatency\_cortControl | 0.09 | 0.09 | 0.35 | -0.50 | 0.66 | 1.00 | 3501.90 | 6160.76 |
| b\_loglatency\_sexm | -0.46 | -0.45 | 0.22 | -0.82 | -0.10 | 1.00 | 5456.02 | 7259.40 |
| b\_loglatency\_age | 0.06 | 0.06 | 0.02 | 0.02 | 0.10 | 1.00 | 5242.87 | 6844.75 |
| b\_loglatency\_test\_type1VS3:tempHot | -0.03 | -0.03 | 0.30 | -0.52 | 0.46 | 1.00 | 5246.33 | 7514.61 |
| b\_loglatency\_test\_type2VS4:tempHot | -0.18 | -0.18 | 0.30 | -0.67 | 0.31 | 1.00 | 5432.60 | 8115.85 |
| b\_loglatency\_test\_type2VS3:tempHot | -0.25 | -0.25 | 0.30 | -0.74 | 0.25 | 1.00 | 5517.51 | 7473.31 |
| b\_loglatency\_test\_type3VS4:tempHot | -0.10 | -0.11 | 0.30 | -0.60 | 0.39 | 1.00 | 5247.17 | 7570.16 |
| b\_loglatency\_test\_type1VS3:cortControl | 0.04 | 0.04 | 0.29 | -0.43 | 0.53 | 1.00 | 5376.57 | 7715.18 |
| b\_loglatency\_test\_type2VS4:cortControl | 0.15 | 0.16 | 0.29 | -0.33 | 0.64 | 1.00 | 5492.31 | 8062.19 |
| b\_loglatency\_test\_type2VS3:cortControl | -0.04 | -0.04 | 0.29 | -0.52 | 0.44 | 1.00 | 5459.05 | 7755.73 |
| b\_loglatency\_test\_type3VS4:cortControl | -0.38 | -0.38 | 0.29 | -0.87 | 0.09 | 1.00 | 5264.74 | 8063.37 |
| b\_loglatency\_tempHot:cortControl | -0.78 | -0.78 | 0.49 | -1.58 | 0.03 | 1.00 | 3491.24 | 5908.08 |
| b\_loglatency\_test\_type1VS3:tempHot:cortControl | 0.25 | 0.25 | 0.42 | -0.43 | 0.94 | 1.00 | 5103.28 | 7366.37 |
| b\_loglatency\_test\_type2VS4:tempHot:cortControl | 0.28 | 0.28 | 0.42 | -0.40 | 0.97 | 1.00 | 4860.78 | 7733.09 |
| b\_loglatency\_test\_type2VS3:tempHot:cortControl | 0.37 | 0.37 | 0.42 | -0.32 | 1.05 | 1.00 | 5243.01 | 8532.21 |
| b\_loglatency\_test\_type3VS4:tempHot:cortControl | 0.74 | 0.75 | 0.42 | 0.05 | 1.44 | 1.00 | 5119.54 | 7726.59 |

*Table S3B.- Summary of the model fitted for Choice*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_choice\_Intercept | -0.68 | -0.68 | 0.58 | -1.64 | 0.26 | 1.00 | 4717.07 | 6912.29 |
| b\_choice\_test\_type1VS3 | 0.24 | 0.24 | 0.69 | -0.89 | 1.38 | 1.00 | 5106.43 | 7093.98 |
| b\_choice\_test\_type2VS4 | 0.71 | 0.70 | 0.69 | -0.42 | 1.86 | 1.00 | 4984.93 | 7514.81 |
| b\_choice\_test\_type2VS3 | 1.12 | 1.10 | 0.73 | -0.06 | 2.35 | 1.00 | 4902.86 | 6926.45 |
| b\_choice\_test\_type3VS4 | 0.33 | 0.32 | 0.70 | -0.82 | 1.48 | 1.00 | 5219.20 | 7158.11 |
| b\_choice\_tempHot | 1.13 | 1.12 | 0.83 | -0.23 | 2.50 | 1.00 | 4283.18 | 6599.41 |
| b\_choice\_cortControl | 0.61 | 0.60 | 0.74 | -0.59 | 1.84 | 1.00 | 3922.51 | 6114.01 |
| b\_choice\_sexm | -0.06 | -0.06 | 0.30 | -0.54 | 0.43 | 1.00 | 14505.46 | 8697.98 |
| b\_choice\_age | -0.04 | -0.04 | 0.03 | -0.09 | 0.01 | 1.00 | 12392.71 | 8820.47 |
| b\_choice\_test\_type1VS3:tempHot | 0.80 | 0.79 | 1.04 | -0.88 | 2.55 | 1.00 | 4972.18 | 6745.87 |
| b\_choice\_test\_type2VS4:tempHot | -1.33 | -1.33 | 1.00 | -2.98 | 0.29 | 1.00 | 4886.89 | 7191.48 |
| b\_choice\_test\_type2VS3:tempHot | -1.77 | -1.77 | 1.04 | -3.49 | -0.09 | 1.00 | 4289.06 | 6024.53 |
| b\_choice\_test\_type3VS4:tempHot | -0.13 | -0.13 | 1.02 | -1.80 | 1.57 | 1.00 | 4538.82 | 7185.57 |
| b\_choice\_test\_type1VS3:cortControl | 0.48 | 0.47 | 0.99 | -1.15 | 2.12 | 1.00 | 4938.94 | 7818.41 |
| b\_choice\_test\_type2VS4:cortControl | -0.70 | -0.69 | 0.98 | -2.32 | 0.90 | 1.00 | 4749.40 | 7672.85 |
| b\_choice\_test\_type2VS3:cortControl | 0.15 | 0.16 | 1.04 | -1.53 | 1.85 | 1.00 | 4980.80 | 8127.50 |
| b\_choice\_test\_type3VS4:cortControl | 0.14 | 0.13 | 1.00 | -1.50 | 1.77 | 1.00 | 4881.82 | 7388.95 |
| b\_choice\_tempHot:cortControl | -1.33 | -1.32 | 1.06 | -3.06 | 0.40 | 1.00 | 3598.45 | 6418.88 |
| b\_choice\_test\_type1VS3:tempHot:cortControl | -0.65 | -0.64 | 1.44 | -3.01 | 1.71 | 1.00 | 4947.05 | 7258.07 |
| b\_choice\_test\_type2VS4:tempHot:cortControl | 1.82 | 1.79 | 1.41 | -0.52 | 4.12 | 1.00 | 4832.87 | 7213.76 |
| b\_choice\_test\_type2VS3:tempHot:cortControl | 0.25 | 0.25 | 1.45 | -2.12 | 2.59 | 1.00 | 4689.39 | 7011.19 |
| b\_choice\_test\_type3VS4:tempHot:cortControl | 0.81 | 0.80 | 1.44 | -1.57 | 3.20 | 1.00 | 4767.29 | 7038.46 |

*Table S3C.- Summary of the model fitted for Interest*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_comparedinterest\_Intercept | 12.58 | 12.75 | 20.03 | -20.62 | 45.52 | 1.00 | 4226.87 | 6914.84 |
| b\_comparedinterest\_test\_type1VS3 | -27.45 | -27.46 | 24.85 | -68.46 | 13.12 | 1.00 | 5057.66 | 7251.20 |
| b\_comparedinterest\_test\_type2VS4 | 4.45 | 4.37 | 25.04 | -36.11 | 45.40 | 1.00 | 4955.22 | 7144.03 |
| b\_comparedinterest\_test\_type2VS3 | -18.02 | -18.08 | 25.03 | -59.03 | 23.55 | 1.00 | 4608.81 | 7655.14 |
| b\_comparedinterest\_test\_type3VS4 | -38.45 | -38.44 | 25.60 | -80.23 | 3.89 | 1.00 | 4974.12 | 7540.36 |
| b\_comparedinterest\_tempHot | -21.42 | -21.25 | 28.74 | -68.59 | 25.65 | 1.00 | 3724.65 | 6038.13 |
| b\_comparedinterest\_cortControl | -10.87 | -10.78 | 25.67 | -53.25 | 31.15 | 1.00 | 3414.61 | 5708.73 |
| b\_comparedinterest\_sexm | -8.60 | -8.64 | 9.32 | -23.92 | 7.03 | 1.00 | 17607.01 | 8664.01 |
| b\_comparedinterest\_age | -0.68 | -0.67 | 0.97 | -2.25 | 0.91 | 1.00 | 15664.51 | 9250.40 |
| b\_comparedinterest\_test\_type1VS3:tempHot | 71.62 | 71.63 | 35.19 | 13.31 | 129.60 | 1.00 | 4600.90 | 6586.40 |
| b\_comparedinterest\_test\_type2VS4:tempHot | -1.40 | -1.38 | 35.97 | -59.74 | 58.37 | 1.00 | 4594.12 | 6529.68 |
| b\_comparedinterest\_test\_type2VS3:tempHot | 34.51 | 34.43 | 35.89 | -23.35 | 93.63 | 1.00 | 4206.05 | 6855.33 |
| b\_comparedinterest\_test\_type3VS4:tempHot | 37.54 | 37.66 | 36.94 | -22.35 | 97.98 | 1.00 | 4702.14 | 7554.35 |
| b\_comparedinterest\_test\_type1VS3:cortControl | 27.46 | 27.64 | 35.35 | -30.54 | 86.37 | 1.00 | 4866.97 | 7599.14 |
| b\_comparedinterest\_test\_type2VS4:cortControl | -5.20 | -5.27 | 35.16 | -62.72 | 52.41 | 1.00 | 4362.77 | 6797.39 |
| b\_comparedinterest\_test\_type2VS3:cortControl | 48.43 | 48.30 | 35.49 | -9.54 | 106.81 | 1.00 | 4047.11 | 6637.73 |
| b\_comparedinterest\_test\_type3VS4:cortControl | 63.11 | 62.88 | 35.72 | 4.22 | 122.72 | 1.00 | 4618.01 | 7533.53 |
| b\_comparedinterest\_tempHot:cortControl | 19.41 | 19.72 | 36.63 | -40.29 | 79.85 | 1.00 | 3346.75 | 5960.45 |
| b\_comparedinterest\_test\_type1VS3:tempHot:cortControl | -75.56 | -75.33 | 50.52 | -157.46 | 7.56 | 1.00 | 4608.18 | 7070.71 |
| b\_comparedinterest\_test\_type2VS4:tempHot:cortControl | 15.19 | 15.16 | 50.30 | -69.06 | 97.00 | 1.00 | 4217.24 | 6394.78 |
| b\_comparedinterest\_test\_type2VS3:tempHot:cortControl | -89.54 | -88.78 | 50.35 | -173.98 | -6.66 | 1.00 | 3896.04 | 6636.15 |
| b\_comparedinterest\_test\_type3VS4:tempHot:cortControl | -43.38 | -43.71 | 51.44 | -127.24 | 41.39 | 1.00 | 4491.70 | 6562.71 |

*Table S3D.- Summary of the model fitted for other effects*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| sd\_clutch\_\_loglatency\_Intercept | 0.34 | 0.34 | 0.19 | 0.04 | 0.67 | 1.01 | 716.16 | 2313.13 |
| sd\_lizard\_id\_\_loglatency\_Intercept | 0.81 | 0.81 | 0.10 | 0.64 | 0.97 | 1.00 | 1725.51 | 2777.99 |
| sd\_clutch\_\_choice\_Intercept | 0.26 | 0.23 | 0.18 | 0.02 | 0.60 | 1.00 | 3913.70 | 5803.67 |
| sd\_lizard\_id\_\_choice\_Intercept | 0.59 | 0.60 | 0.25 | 0.13 | 0.99 | 1.00 | 2047.51 | 3110.77 |
| sd\_clutch\_\_comparedinterest\_Intercept | 9.92 | 9.22 | 6.32 | 1.03 | 21.27 | 1.00 | 4065.36 | 6333.93 |
| sd\_lizard\_id\_\_comparedinterest\_Intercept | 9.31 | 8.34 | 6.38 | 0.81 | 20.85 | 1.00 | 3847.09 | 5748.30 |
| sigma\_loglatency | 0.65 | 0.65 | 0.03 | 0.61 | 0.70 | 1.00 | 12611.43 | 8861.89 |
| sigma\_comparedinterest | 78.78 | 78.70 | 3.03 | 73.99 | 83.90 | 1.00 | 15359.76 | 8383.11 |
| lprior | -29.26 | -29.25 | 0.08 | -29.40 | -29.13 | 1.00 | 8343.29 | 9738.65 |
| lp\_\_ | -3440.63 | -3440.02 | 18.68 | -3472.06 | -3410.58 | 1.00 | 2890.39 | 5974.94 |

#### Testing potential side biases

*Table S4.- Number of individuals per treatment that chose the right (R) or left (L) side in each of the numerical tests. p-value indicates the result of the binomial test comparing the number of choices between sides.*

|  | 1 VS 4 | 1 VS 3 | 2 VS 4 | 2 VS 3 | 3 VS 4 |
| --- | --- | --- | --- | --- | --- |
| Control-Cold (n = 20) | R = 12 | L = 8 , p = 0.5 | R = 12 | L = 8 , p = 0.5 | R = 9 | L = 11 , p = 0.82 | R = 12 | L = 8 , p = 0.5 | R = 12 | L = 8 , p = 0.5 |
| Control-Hot (n = 20) | R = 12 | L = 8 , p = 0.5 | R = 5 | L = 15 , p = 0.04 | R = 9 | L = 11 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |
| CORT-Cold (n = 20) | R = 11 | L = 9 , p = 0.82 | R = 11 | L = 9 , p = 0.82 | R = 11 | L = 9 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |
| CORT-Hot (n = 20) | R = 11 | L = 9 , p = 0.82 | R = 9 | L = 11 , p = 0.82 | R = 9 | L = 11 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |

#### Control of size in both options

On the videos of half of the lizards, we estimated the length of both options using the ruler tool on Photoshop 2024. For each choice in each test, we first calibrated the masure of one centimeter using the length of the bottom of the platform (see Fig below). After calibrating, we measured the length of the crickets at their maximum length, trying to keep the line parallel to the bottom of the platform (see below). The results are shown in Table S4.

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| Fig 3— Calibration of the ruler tool in Photoshop 2024. The bottom of the platform was used to calibrate the ruler tool to measure the length of the crickets. |

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| Fig 4— Measurement of the length of the crickets. The ruler tool was used to measure the length of the crickets at their maximum length. |

*Table S4.- Mean length (cm) of the crickets in each of the numerical tests. The difference in length between the two options is also shown, with the 95% CI.*

| Test | Mean length small (cm) | Mean length large (cm) | Mean differences in length | 95% CI differences in length |
| --- | --- | --- | --- | --- |
| 1 VS 3 | 0.81 | 1.53 | 0.72 | [0.31 , 1.15] |
| 1 VS 4 | 0.81 | 1.86 | 1.05 | [0.61 , 1.61] |
| 2 VS 3 | 1.72 | 1.58 | -0.14 | [-0.61 , 0.32] |
| 2 VS 4 | 1.76 | 1.85 | 0.10 | [-0.23 , 0.56] |
| 3 VS 4 | 1.55 | 1.85 | 0.30 | [-0.19 , 0.89] |

#### Prey orientation test

We performed a choice test to investigate if the orientation of crickets affected the lizards’ choice. We used the same platform and Petri dish as in the numerical discrimination task, but we placed one cricket on each side of the platform, one oriented vertically in respect to the shelter position (see [Fig. 1](#fig-Methods) B) and the other one horizontal to the shelter. We performed a unique trial randomising the position of the orientation of the cricket. We recorded the number of individuals that chose the cricket oriented vertically and horizontally. Results are shown in the table below.

*Table S4.- Number of individuals per treatment that chose the cricket oriented horizontally (Horizontal) or vertically (Vertical) in our control tests. p-value indicates the result of the binomial test comparing the number of choices between both choices.*

|  | Horizontal | Vertical | p-value |
| --- | --- | --- | --- |
| Cold-Control (n = 20) | 8 | 12 | 0.503 |
| Hot-Control (n = 20) | 7 | 13 | 0.263 |
| Cold-CORT (n = 20) | 12 | 8 | 0.503 |
| Hot-CORT (n = 20) | 9 | 11 | 0.824 |

#### Searching for relevant literature

To look for relevant literature about the effects of early environment on numerical discrimination, we searched in the Web of Science and Scopus using the terms on respectively. The queries employed are detailed below. We looked for manuscripts for all years available. The last search was conducted on the 11th of October 2024; the results below refer to this last search.

We found 24 articles on Web of Science and 22 on Scopus, plus one preprint on Scopus. Out of all the documents, only one study was relevant to our search: Vila-Pouca et al. ([2019](#ref-vila_pouca_quantity_2019)). That study appeared in both databases and was the only one that explored the effects of early environment on numerical abilities.

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| Fig 3— Search query on Web of Science. |

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| Fig 4— Search query on Scopus. |

#### Checking the model plots

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